

# The Size Variance Relationship of Business Firm Growth Rates

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**The relationship between the size and the variance of firm growth rates is known to follow an approximate power-law behavior  $\sigma(S) \sim S^{-\beta(S)}$  where  $S$  is the firm size and  $\beta(S) \approx 0.2$  is an exponent weakly dependent on  $S$ . Here we show how a model of proportional growth which treats firms as classes composed of various number of units of variable size, can explain this size-variance dependence. In general, the model predicts that  $\beta(S)$  must exhibit a crossover from  $\beta(0) = 0$  to  $\beta(\infty) = 1/2$ . For a realistic set of parameters,  $\beta(S)$  is approximately constant and can vary in the range from 0.14 to 0.2 depending on the average number of units in the firm. We test the model with a unique industry specific database in which firm sales are given in terms of the sum of the sales of all their products. We find that the model is consistent with the empirically observed size-variance relationship.**

Firm growth | Proportional growth | Size variance relationship

## Introduction

Gibrat was probably the first who noticed the skew size distributions of business firms (1). As a simple candidate explanation he postulated the “Law of Proportionate Effect” according to which the expected value of the growth rate of a business firm is proportional to the current size of the firm (2). Several models of proportional growth have been subsequently introduced in economics (3; 4; 5; 6). In particular, Simon and colleagues (7; 8) examined a stochastic process for Bose-Einstein statistics similar to the one originally proposed by Yule (9) to explain the distribution of sizes of genera. The Law of Proportionate Effect implies that the variance  $\sigma^2$  of firm growth rates is independent of size, while according to the Simon model it is inversely proportional to the size of business firms. The two predictions have not been confirmed empirically and following Stanley and colleagues (10) several scholars (11; 12) have recently found a non-trivial relationship between the size of the firm  $S$  and the variance  $\sigma^2$  of its growth rate  $\sigma \sim S^{-\beta}$  with  $\beta \approx 0.2$ .

Numerous attempts have been made to explain this puzzling evidence by considering firms as collection of independent units of uneven size (10; 12; 13; 14; 15; 16; 17; 18) but existing models do not provide a unifying explanation for the probability density functions of the growth and size of firms as well as the size variance relationship. Thus, the scaling of the variance of firm growth rates is still an unsolved problem in economics (19; 20). Recent papers (21; 22; 23; 24; 25) provide a general framework for the growth and size of business firms based on the number and size distribution of their constituent parts (12; 13; 14; 15; 21; 26; 27; 28; 29). Specifically, Fu and colleagues (21) present a model of proportional growth in both the number of units and their size, drawing some general implications on the mechanisms which sustain business firm growth. The model in (21) accurately predicts the shape of the distribution of the growth rates (21; 22) and the size distribution of firms (23). In this paper we derive the implications of the model in (21) on the size-variance relationship. The main conclusion is that the size variance relationship is

not a true power law with a single well-defined exponent  $\beta$  but undergoes a slow crossover from  $\beta = 0$  for  $S \rightarrow 0$  to  $\beta = 1/2$  for  $S \rightarrow \infty$ . The predictions of the model are tested in both real world and simulation settings.

## The Model

In the model presented in (21) and summarized in the Supplemental Information firms consist of a random number of units of variable size. The number of units  $K$  is defined as in the Simon model. The size of the units  $\xi$  evolves according to a multiplicative brownian motion (Gibrat process). Thus both the growth distribution,  $P_\eta$ , and the size distribution,  $P_\xi$ , of the units are lognormal.

To derive the size variance relationship we must compute the conditional probability density of the growth rate  $P(g|S, K)$ , of a firm with  $K$  units and size  $S$ . For  $K \rightarrow \infty$  the conditional probability density function  $P(g|S, K)$  develops a tent shape functional form, because in the center it converges to a Gaussian distribution with the width decreasing inverse proportionally to  $\sqrt{K}$ , while the tails are governed by the behavior of the growth distribution of a single unit which remains to be wide independently of  $K$ .

We can also compute the conditional probability  $P(S|K)$ , which is the convolution of  $K$  unit size distributions  $P_\xi$ . In case of lognormal  $P_\xi$  with a large logarithmic variance  $V_\xi$  and mean  $m_\xi$ , the convergence of  $P(S|K)$  to a Gaussian is very slow (23). Since  $P(S, K) = P(S|K)P(K)$ , we can find

$$P(g|S) = \sum P(g|S, K)P(S|K)P(K), \quad [1]$$

where all the distributions  $P(g|S, K)$ ,  $P(S|K)$ ,  $P(K)$  can be found from the parameters of the model.  $P(S|K)$  has a sharp maximum near  $S = S_K \equiv K\mu_\xi$ , where  $\mu_\xi = \exp(m_\xi + V_\xi/2)$  is the mean of the lognormal distribution of the unit sizes. Conversely,  $P(S|K)$  as function of  $K$  has a sharp maximum near  $K_S = S/\mu_\xi$ . For the values of  $S$  such that  $P(K_S) \gg 0$ ,  $P(g|S) \approx P(g|K_S)$ , because  $P(S|K)$  serves as a  $\delta(K - K_S)$  so that only terms with  $K \approx K_S$  make a dominant contribution to the sum of Eq. (1). Accordingly, one can approximate  $P(g|S)$  by  $P(g|K_S)$  and  $\sigma(S)$  by  $\sigma(K_S)$ . However, all firms with  $S < S_1 = \mu_\xi$  consist essentially of only one unit and thus

$$\sigma(S) = \sqrt{V_\eta} \quad [2]$$

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for  $S < \mu_\xi$ . For large  $S$  if  $P(K_S) > 0$

$$\sigma(S) = \sigma(K_S) = \sqrt{V/K_S} = \frac{\exp(3V_\xi/4 + m_\xi/2)\sqrt{\exp(V_\eta) - 1}}{\sqrt{S}} \quad [3]$$

where  $m_\eta$  and  $V_\eta$  are the logarithmic mean and variance of the unit growth distributions  $P_\eta$  and  $V = \exp(V_\xi)[\exp(V_\eta) - 1]$ , as in (21). Thus one expects to have a crossover from  $\beta = 0$  for  $S < \mu_\xi$  to  $\beta = 1/2$  for  $S \gg S^*$ , where

$$S^* = \exp(3V_\xi/2 + m_\xi)(\exp(V_\eta) - 1)/V_\eta \quad [4]$$

is the value of  $S$  for which Eq.(2) and Eq.(3) give the same value of  $\sigma(S)$ . Note that for small  $V_\eta < 1$ ,  $S^* \approx \exp(3V_\xi/2 + m_\xi)$ . The range of crossover extends from  $S_1$  to  $S^*$ , with  $S^*/S_1 = \exp(V_\xi) \rightarrow \infty$  for  $V_\xi \rightarrow \infty$ . Thus in the double logarithmic plot of  $\sigma$  vs.  $S$  one can find a wide region in which the slope  $\beta$  slowly vary from 0 to 1/2 ( $\beta \approx 0.2$ ) in agreement with many empirical observations.

The crossover to  $\beta = 1/2$  will be observed only if  $K^* = S^*/\mu_\xi = \exp(V_\xi)$  is such that  $P(K^*)$  is significantly larger than zero. For the distribution  $P(K)$  with a sharp exponential cutoff  $K = K_0$ , the crossover will be observed only if  $K_0 \gg \exp(V_\xi)$ .

Two scenarios are possible for  $S > S_0 = K_0\mu_\xi$ . In the first, there will be no firms with  $S \gg S_0$ . In the second, if the distribution of the size of units  $P_\xi$  is very broad, large firms can exist just because the size of a unit can be larger than  $S_0$ . In this case exceptionally large firms might consist of one extremely large unit  $\xi_{\max}$ , whose fluctuations dominate the fluctuations of the entire firm.

One can introduce the effective number of units in a firm  $K_e = S/\xi_{\max}$ , where  $\xi_{\max}$  is the largest unit of the firm. If  $K_e < 2$ , we would expect that  $\sigma(S)$  will again become equal to its value for small  $S$  given by Eq. (2), which means that under certain conditions  $\sigma(S)$  will start to increase for very large firms and eventually becomes the same as for small firms.

Whether such a scenario is possible depends on the complex interplay of  $V_\xi$  and  $P(K)$ . The crossover to  $\beta = 1/2$  will be seen only if  $P(K > K^*) > P(\xi > S^*)$  which means that such large firms predominantly consist of a large number of units. Taking into account the equation of  $P_\xi$ , one can see that  $P(\xi > S^*) \sim \exp(-9/8V_\xi)$ .

On the one hand, for an exponential  $P(K)$ , this implies that  $\exp(-\exp(V_\xi)/K_0) > \exp(-9/8V_\xi)$  or

$$V_\xi > 8\exp(V_\xi)/(9K_0). \quad [5]$$

This condition is easily violated if  $V_\xi \gg \ln K_0$ . Thus for the distributions  $P(K)$  with exponential cut-off we will never see the crossover to  $\beta = 1/2$  if  $V_\xi \gg \ln K_0$ .

On the other hand, for a power law distribution  $P(K) \sim K^{-\phi}$ , the condition of the crossover becomes  $\exp(V_\xi)^{1-\phi} > \exp(-9/8V_\xi)$ , or  $(\phi - 1)V_\xi < 9/8V_\xi$  which is rigorously satisfied for

$$\phi < 17/8 \quad [6]$$

but even for larger  $\phi$  is not dramatically violated. Thus for power law distributions, we expect a crossover to  $\beta = 1/2$  for large  $S$  and significantly large number  $N$  of firms in the data set:  $NP(K^*) > 1$ . The sharpness of the crossover mostly depends on  $V_\xi$ . For power law distributions we expect a sharper crossover than for exponential ones because the majority of firms in a power law distribution have a small number of products  $K$ , and hence  $\beta = 0$  almost up to  $S^*$ , the size at which the crossover is observed. For exponential distributions we expect a slow crossover which is interrupted if  $V_\xi$  is comparable to  $\ln K_0$ . For  $S \gg S_1$  this crossover is well represented by the behavior of  $\sigma(K_S)$ .

We confirm these heuristic arguments by means of computer simulations (see the Supplemental Information).

Figures 1 and 5 illustrate the importance of the effective number of units  $K_e$ . When  $K_S$  becomes larger than  $K_0$ ,  $\sigma(S)$  starts to follow  $\sigma(K_e)$ . Accordingly, for very large firms  $\sigma(S)$  becomes almost the same as for small firms. The maximal negative value of the slope  $\beta_{\max}$  of the double logarithmic graphs presented in Fig. 1(a) correspond to the inflection points of these graphs, and can be identified as approximate values of  $\beta$  for different values of  $K_0$ . One can see that  $\beta_{\max}$  increases as  $K_0$  increases from a small value close to 0 for  $K_0 = 10$  to a value close to 1/2 for  $K_0 = 10^5$  in agreement with the predictions of the central limit theorem.

To further explore the effect of the  $P(K)$  on the size-variance relationship we select  $P(K)$  to be a pure power law  $P(K) \sim K^{-2}$  [Fig. 2(a)]. Moreover, we consider a realistic  $P(K)$  where  $K$  is the number of products by firms in the pharmaceutical industry [Fig. 2(b)]. This distribution can be well approximated by a Yule distribution with  $\phi = 2$  and an exponential cut-off for large  $K$ . Figure 2 shows that, for a scale-free power-law distribution  $P(K)$ , the size variance relationship depicts a steep crossover from  $\sigma = \sqrt{V_\eta}$  given by Eq. (2) for small  $S$  to  $\sigma = \sqrt{V/K_S}$  given by Eq. (3) for large  $S$ , for any value of  $V_\xi$ .

As we see, the size-variance relationship of firms  $\sigma(S)$  can be well approximated by the behavior of  $\sigma(K_S)$  [Fig 1(a)]. It was shown in (24) that, for realistic  $V_\xi$ ,  $\sigma^2(K)$  can be approximated in a wide range of  $K$  as  $\sigma(K) \sim K^{-\beta}$  with  $\beta \approx 0.2$ , which eventually crosses over to  $K^{-1/2}$  for large  $K$ . In other words, one can write  $\sigma(K) \sim K^{-\beta(K)}$  where  $\beta(K)$ , defined as the slope of  $\sigma(K)$  on a double logarithmic plot, increases from a small value dependent on  $V_\xi$  at small  $K$  to 1/2 for  $K \rightarrow \infty$ . Accordingly, one can expect the same behavior for  $\sigma(S)$  for  $K_S < K_0$ .

Thus it would be desirable to derive an exact analytical expression for  $\sigma(K)$  in case of lognormal and independent  $P_\xi$  and  $P_\eta$ . Unfortunately the radius of convergence of the expansion of a logarithmic growth rate in inverse powers of  $K$  is equal to zero, and these expansions have only a formal asymptotic meaning for  $K \rightarrow \infty$ . However, these expansions are useful since they demonstrate that  $\mu$  and  $\sigma$  do not depend on  $m_\eta$  and  $m_\xi$  except for the leading term in  $\mu$ :  $m_0 = m_\eta + V_\eta/2$ . Not being able to derive close-form expressions for  $\sigma$  (see Supplemental Information), we perform extensive computer simulations, where  $\xi$  and  $\eta$  are independent random variables taken from lognormal distributions  $P_\xi$  and  $P_\eta$  with different  $V_\xi$  and  $V_\eta$ . The numerical results (Fig. 3) suggest that

$$\ln \sigma^2(K)K/C \approx F_\sigma[\ln(K) - f(V_\xi, V_\eta)], \quad [7]$$

where  $F_\sigma(z)$  is a universal scaling function describing a crossover from  $F_\sigma(z) \rightarrow 0$  for  $z \rightarrow \infty$  to  $F_\sigma(z)/z \rightarrow 1$  for  $z \rightarrow -\infty$  and  $f(V_\xi, V_\eta) \approx f_\xi(V_\xi) + f_\eta(V_\eta)$  are functions of  $V_\xi$  and  $V_\eta$  which have linear asymptotes for  $V_\xi \rightarrow \infty$  and  $V_\eta \rightarrow \infty$  [Fig. 3(b)].

Accordingly, we can try to define  $\beta(z) = (1 - dF_\sigma/dz)/2$  [Fig. 4 (a)]. The main curve  $\beta(z)$  can be approximated by an inverse linear function of  $z$ , when  $z \rightarrow -\infty$  and by a stretched exponential as it approaches the asymptotic value 1/2 for  $z \rightarrow +\infty$ . The particular analytical shapes for these asymptotes are not known and derived solely from least square fitting of the numerical data. The scaling for  $\beta(z)$  is only approximate with significant deviations from a universal curve for small  $K$ . The minimal value for  $\beta$  practically does not depend on  $V_\eta$  and is approximately inverse proportional to a linear function of  $V_\xi$ :

$$\beta_{\min} = \frac{1}{pV_\xi + q} \quad [8]$$

where  $p \approx 0.54$  and  $q \approx 2.66$  are universal values [Fig. 4(b)]. This finding is significant for our study, since it indicates that near its minimum,  $\beta(K)$  has a region of approximate constancy with the value  $\beta_{min}$  between 0.14 and 0.2 for  $V_\xi$  between 4 and 8. These values of  $V_\xi$  are quite realistic and correspond to the distribution of unit sizes spanning over from roughly two to three orders of magnitude (68% of all units), which is the case in the majority in economic and ecological systems. Thus our study provides a reasonable explanation for the abundance of value of  $\beta \approx 0.2$ .

The above analysis shows that  $\sigma(S)$  is not a true power-law function, but undergoes a crossover from  $\beta = \beta_{min}(V_\xi)$  for small firms to  $\beta = 1/2$  for large firms. However this crossover is expected only for very broad distributions  $P(K)$ . If it is very unlikely to find a firm with  $K > K_0$ ,  $\sigma(S)$  will start to grow for  $S > K_0\mu_\xi$ . Empirical data do not show such an increase (Fig. 6), because in reality there are few giant firms which rely on few extremely large units. These firms are extremely volatile and hence unstable. Therefore for real data we do see neither a crossover to  $\beta = 1/2$  nor an increase of  $\sigma$  for large companies.

## The Empirical Evidence

Since the size variance relationship depends on the partition of firms into their constituent components, to properly test our model one must decompose an industrial system into parts. In this section we analyze a unique database, kindly provided by the EPRIS program, which records the sales figures of 916,036 pharmaceutical products commercialized by 7,184 firms worldwide from 1994 to 2004. The database covers the whole size distribution for products and firms and monitors flows of entry and exit at every level of aggregation. Products are classified by companies, markets and international brand names, with different distributions  $P(K)$  with  $\langle K \rangle = K_0$  ranging from 5.8 for international products to almost 1,600 for markets [Tab. 1]. If firms have on average  $K_0$  products and  $V_\xi \ll \ln K_0$ , the scaling variable  $z = K_0$  is positive and we expect  $\beta \rightarrow 1/2$ . On the contrary, if  $V_\xi \gg \ln K_0$ ,  $z < 0$  and we expect  $\beta \rightarrow 0$ . These considerations work only for a broad distribution of  $P(K)$  with mild skewness such as an exponential distribution. At the opposite extreme, if all companies have the same number of products, the distribution of  $S$  is narrowly concentrated near the most probable value  $S_0 = \mu_\xi K$  and there is no reason to define  $\beta(S)$ . Only very rarely  $S \gg S_0$ , due to a low probability of observing an extremely large product which dominates the fluctuation of a firm. Such a firm is more volatile than other firms of equal size. This would imply negative  $\beta$ . If  $P(K)$  is power law distributed, there is a wide range of values of  $K$ , so that there are always firms for which  $\ln K \gg V_\xi$  and we can expect a slow crossover from  $\beta = 0$  for small firms to  $\beta = 1/2$  for large firms, so that for a wide range of empirically plausible  $V_\xi$ ,  $\beta$  is far from  $1/2$  and statistically different from 0. The estimated value of the size-variance scaling coefficient  $\beta$  goes from 0.123 for products to 0.243 for therapeutic markets with companies in the middle (0.188) [Tab. 1 and Fig. 5].

The model in (21) relies upon general assumptions of independence of the growth of products from each other and from the number of products  $K$ . However, these assumptions could be violated and other reasons for the scaling of the size variance relationship such as units interdependence, size and time dependence must be considered (see the Supplemental Information for a discussion of candidate explanations). To discriminate among different plausible explanations we run a set of experiments in which we keep the real  $P(K)$  and ran-

domly reassign products to firms. In the first simulation we randomly reassign products by keeping the real world relationship between the size,  $\xi$ , and growth,  $\eta$ , of products. In the second simulation we reassign also  $\eta$ . Finally in the last simulation we generate elementary units according to a multiplicative brownian motion (Gibrat process) with empirically estimated values of the mean and variance of  $\xi$  and  $\eta$ . Tab. 1 summarizes the results of our simulations.

The first simulation allows us to check for the size dependence and unit interdependence hypotheses by randomly reassigning elementary units to firms and markets. In doing that, we keep the number of the products in each class and the history of the fluctuation of each product sales unchanged. As for the size dependence, our analysis shows that there is indeed strong correlation between the number of products in the company and their average size defined as  $\langle \xi(K) \rangle = \langle \frac{1}{K} \sum_{i=1}^K \xi_i \rangle$  where  $\langle \rangle$  indicates averaging over all companies with  $K$  products. We observe an approximate power law dependence  $\langle \xi(K) \rangle \sim K^\gamma$ , where  $\gamma = 0.38$ . If this would be a true asymptotic power law holding for  $K \rightarrow \infty$  than the average size of the company of  $K$  products would be proportional to  $\xi(K)K \sim K^{1+\gamma}$ . Accordingly, the average number of products in the company of size  $S$  would scale as  $K_0(S) \sim S^{1/(1+\gamma)}$  and consequently due to central limit theorem  $\beta = 1/(2+2\gamma)$ . In our data base, this would mean that the asymptotic value of  $\beta = 0.36$ . Similar logic was used to explain  $\beta$  in (15; 11). Another effect of random redistribution of units will be the removal of possible correlations among  $\eta_i$  in a single firm (unit interdependence). Removal of positive correlations would decrease  $\beta$ , while removal of negative correlations would increase  $\beta$ . The mean correlation coefficient of the product growth rates at the firm level  $\langle \rho(K) \rangle$  also has an approximate power law dependence  $\langle \rho(K) \rangle \sim K^\zeta$ , where  $\zeta = -0.36$ . Since larger firms have bigger products and are more diversified than small firms the size dependence and unit interdependence cancel out and  $\beta$  practically does not change if products are randomly reassigned to firms.

To control the effect of time dependence, we keep the sizes of products  $\xi_i$  and their number  $K_\alpha$  at year  $t$  for each firm  $\alpha$  unchanged, so  $S_t = \sum_{i=1}^{K_\alpha} \xi_i$  is the same as in the empirical data. However, to compute the sales of a firm in the following year  $\tilde{S}_{t+1} = \sum_{i=1}^{K_\alpha} \xi'_i$ , we assume that  $\xi'_i = \xi_i \eta_i$ , where  $\eta_i$  is an annual growth rate of a randomly selected product. The surrogate growth rate  $\tilde{g} = \ln \frac{\tilde{S}_{t+1}}{S_t}$  obtained in this way does not display any size-variance relationship at the level of products ( $\beta_2^* = 0$ ). However, we still observe a size variance relationship at higher levels of aggregation. This test demonstrates that 1/3 of the size variance relationship depends on the growth process at the level of elementary units which is not a pure Gibrat process. However, asynchronous product lifecycles are washed out upon aggregation and there is a persistent size-variance relationship which is not due to product auto-correlation.

Finally we reproduced the model in (21) with the empirically observed  $P(K)$  and the estimated moments of the log-normal distribution of products ( $m_\xi = 7.58$ ,  $V_\xi = 4.41$ ). We generate  $N$  random products according to our model (Gibrat process) with the empirically observed level of  $V_\xi$  and  $m_\xi$ . As we can see in Tab. 1, the model in (21) closely reproduce the values of  $\beta$  at any level of aggregation. We conclude that the model in (21) correctly predicts the size-variance relationship and the way it scales under aggregation.

The variance of the size of the constituent units of the firm  $V_\xi$  and the distribution of units into firms are both relevant to explain the size variance relationship of firm growth rates. Simulations results in Fig. 6 reveal that if elementary units

are of the same size ( $V_\xi = 0$ ) the central limit theorem will work properly and  $\beta \approx 1/2$ . As predicted by our model, by increasing the value of  $V_\xi$  we observe at any level of aggregation the crossover of  $\beta$  from  $1/2$  to  $0$ . The crossover is faster at the level of markets than at the level of products due to the higher average number of units per class  $K_0$ . However, in real world settings the central limit theorem never applies because firms have a small number of components of variable size ( $V_\xi > 0$ ). For empirically plausible values of  $V_\xi$  and  $K_0$   $\beta \approx 0.2$ .

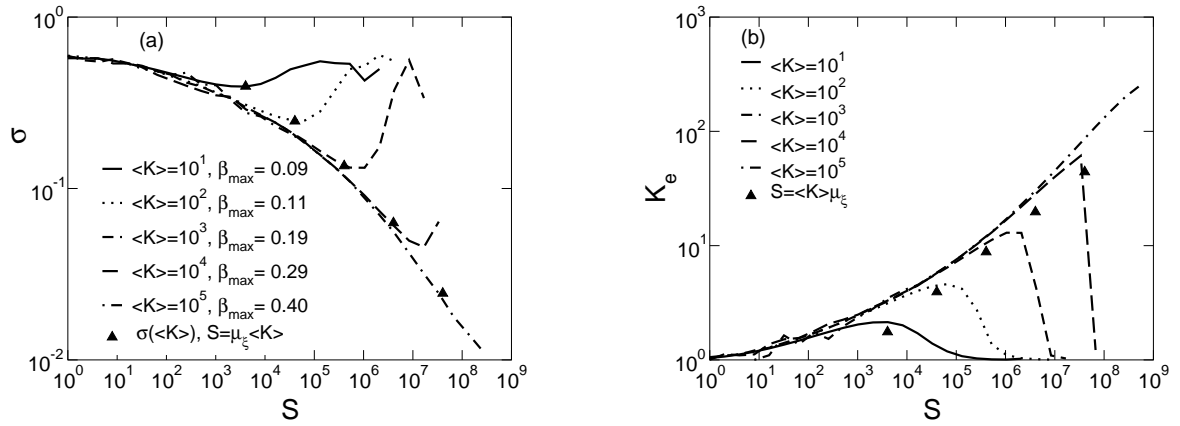
## Discussion

Firms grow over time as the economic system expands and new investment opportunities become available. To capture new business opportunities firms open new plants and launch new products, but the revenues and return to the investments are uncertain. If revenues were independent random variables drawn from a Gaussian distribution with mean  $m_e$  and variance  $V_e$  one should expect that the standard deviation of the sales growth rate of a firm with  $K$  products will be  $\sigma(S) \sim S^{-\beta(S)}$  with  $\beta = 1/2$  and  $S = m_e K$ . On the contrary, if the size of business opportunities is given by a multiplicative brownian motion (Gibrat's process) and revenues are independent random variables drawn from a lognormal distribution with mean  $m_\xi$  and variance  $V_\xi$  the central limit theorem does not work effectively and  $\beta(S)$  exhibits a crossover from  $\beta = 0$  for  $S \rightarrow 0$  to  $\beta = 1/2$  for  $S \rightarrow \infty$ . For realistic distributions of the number and size of business opportunities,  $\beta(S)$  is approximately constant, as it varies in the range from  $0.14$  to  $0.2$  depending on the average number of units in the firm  $K_0$  and the variance of the size of business opportunities  $V_\xi$ . This implies that a firm of size  $S$  is expected to be riskier than the sum of  $S$  firms of size  $1$ , even in the case of constant returns to scale and independent business opportunities.

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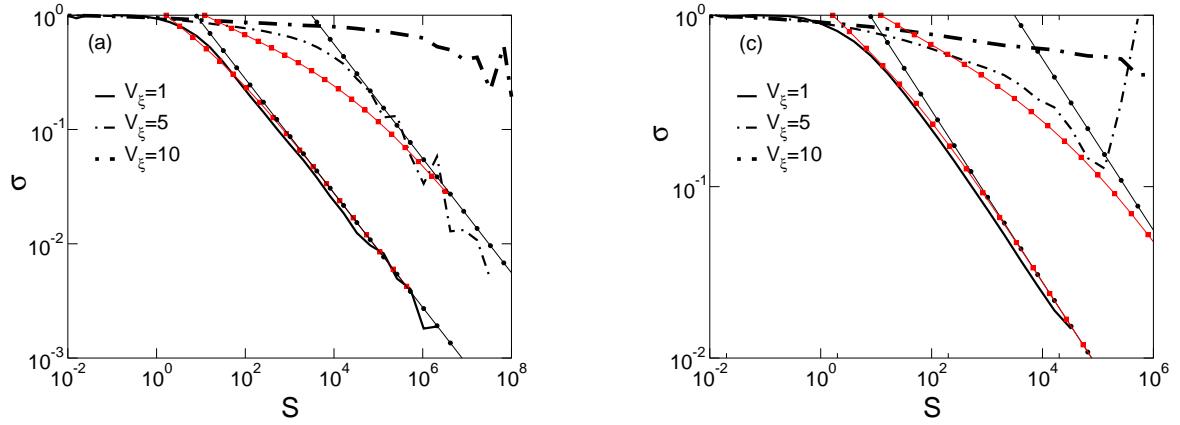
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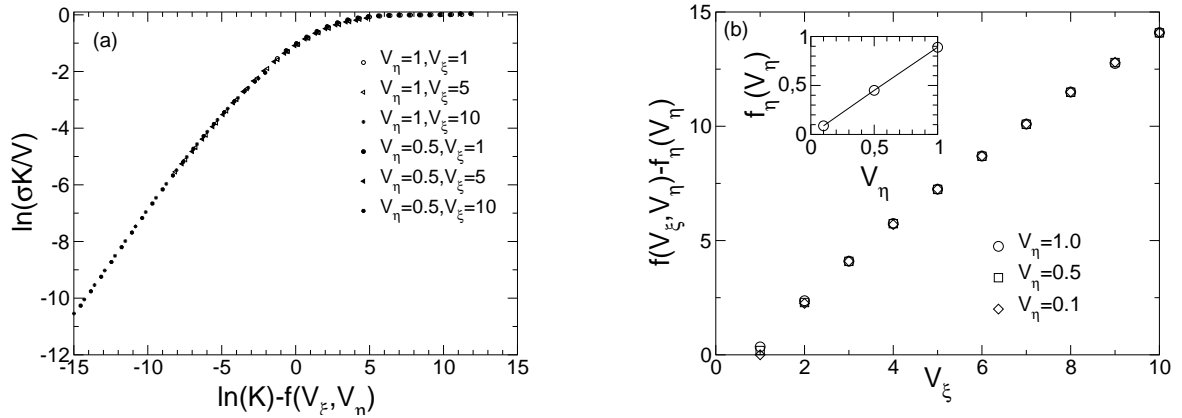
**Fig. 1.** (a) Simulation results for  $\sigma(S)$  according to Eq. (1) for exponential  $P(K) = \exp(-K/K_0)/K_0$  with  $K_0 = 10, 10^2, 10^3, 10^4, 10^5$  and lognormal  $P_\xi$  and  $P_\eta$  with  $V_\xi = 5.13, m_\xi = 3.44, V_\eta = 0.36, \mu_\eta = 0.016$  computed for the pharmaceutical database. One can see that, for small enough  $S$  and for different  $K_0$ ,  $\sigma(S)$  follows a universal curve which can be well approximated with  $\sigma(K_S)$ , with  $K_S = S/\mu_\xi \approx S/405$ . For  $K_S > K_0$ ,  $\sigma(S)$  departs from the universal behavior and starts to increase. This increase can be explained by the decrease of the effective number of units  $K_e(S)$  for the extremely large firms. The maximal negative slope  $\beta_{\max}$  increases as  $K_0$  increases in agreement with the predictions of the central limit theorem. (b) One can see, that  $K_e(S)$  reaches its maximum around  $S \approx K\mu_\xi$ . The positions of maxima in  $K_e(S)$  coincide with the positions of minima in  $\sigma(S)$ .

**Table 1.** The size-variance relationship  $\sigma(S) \sim S^{-\beta(S)}$ : estimated values of  $\beta$  and simulation results  $\beta^*$  at different levels of aggregations from products to markets. In simulation 1 ( $\beta_1^*$ ) products are randomly reassigned to firms and markets. In simulation 2 ( $\beta_2^*$ ) the growth rates of products are reassigned too. In simulation 3 ( $\beta_3^*$ ) we reproduce the model in (21) with real  $P(K)$  and estimated values of  $m_\xi = 7.58$  and  $V_\xi = 2.10$ .

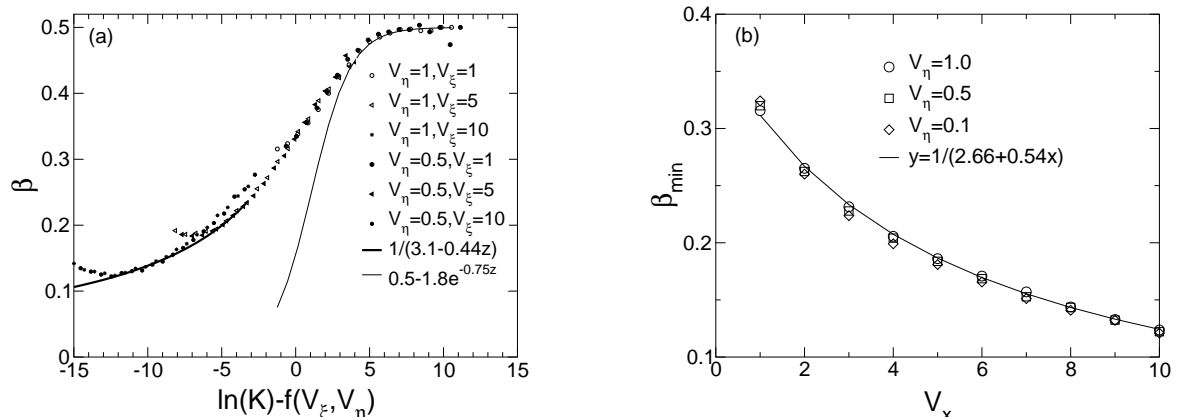
	$N$	$K_0$	$\beta_1$	$\beta_1^*$	$\beta_2^*$	$\beta_3^*$
Markets	574	1,596.9	0.243	0.213	0.232	0.221
Firms	7,184	127.5	0.188	0.196	0.125	0.127
Intl. Products	189,302	5.8	0.151	0.175	0.038	0.020
All Products	916,036	–	0.123	0.123	0	0



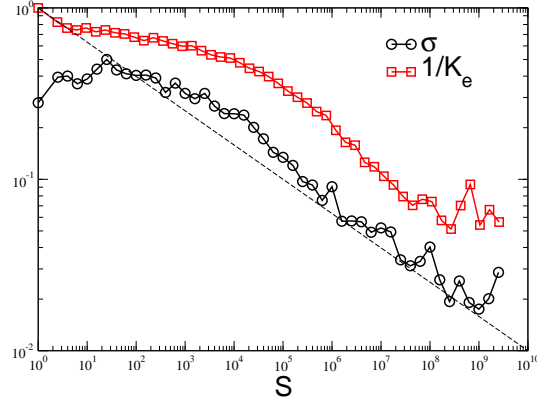
**Fig. 2.** Size variance relationship  $\sigma(S)$  for various  $V_\xi$  with  $P(K) \sim K^{-2}$  (a) and real  $P(K)$  (b). A sharp crossover from  $\beta = 0$  to  $\beta = 1/2$  is seen for the power law distribution even for large values of  $V_\xi$ . In case of real  $P(K)$  one can see a wide crossover regions in which  $\sigma(S)$  can be approximated by a power-law relationship with  $0 < \beta < 1/2$ . Note that the slope of the graphs ( $\beta$ ) decreases with the increase of  $V_\xi$ . The graphs of  $\beta(K_S)$  and their asymptotes are also shown with squares and circles, respectively.



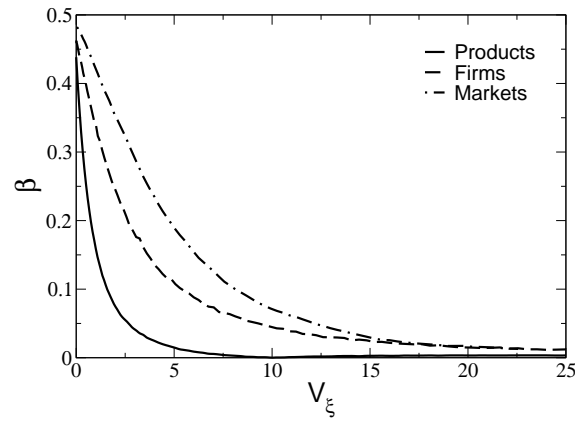
**Fig. 3.** (a) Simulation results for  $\sigma^2(K)$  in case of lognormal  $P_\xi$  and  $P_\eta$  and different  $V_\xi$  and  $V_\eta$  plotted on a universal scaling plot as a functions of scaling variable  $z = \ln(K) - f(V_\xi, V_\eta)$ . (b) The shift function  $f(V_\xi, V_\eta)$ . The graph shows that  $f(V_\xi, V_\eta) \approx f_\xi(V_\xi) + f_\eta(V_\eta)$ . Both  $f_\xi(V_\xi)$  and  $f_\eta(V_\eta)$  (inset) are approximately linear functions.



**Fig. 4.** (a) The effective exponent  $\beta(z)$  obtained by differentiation of  $\sigma^2(z)$  plotted in Fig. 3 (a). Solid lines indicate least square fits for the left and right asymptotes. The graph shows significant deviations of  $\beta(K, V_\xi, V_\eta)$  from a universal function  $\beta(z)$  for small  $K$ , where  $\beta(K)$  develops minima. (b) The dependence of the minimal value of  $\beta_{min}$  on  $V_\xi$ . One can see that this value practically does not depend on  $V_\eta$  and is inverse proportional to the linear function of  $V_\xi$ .



**Fig. 5.** The standard error of firm growth rates ( $\sigma$ ) (circles), and the share of the largest products ( $1/K_e$ ) (squares) versus the size of the firm ( $S$ ). As predicted by our model for  $S < S_1 = \mu_\xi \approx 3.44$ ,  $\beta \approx 0$ . For  $S > S_1$   $\beta$  increases but never reaches  $1/2$  due to the slow growth of the effective number of products ( $K_e$ ). The flattening of the upper tail is due to some large companies with unusually large products.



**Fig. 6.** The scaling of the size-variance relationship as a function of  $V_\xi$ .  $\beta$  decays rapidly from  $1/2$  to  $0$  for  $V_\xi \rightarrow \infty$ . In the simulation we keep the real  $P(K)$  for products, companies and markets and assign products drawn from a lognormal distribution with the empirically observed mean  $m_\xi$  and variance  $0 < V_\xi \leq 25$ .

# Supplemental Information

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The purpose of this Supplemental Information is to describe the model presented by Fu and colleagues (1) and summarize the empirical evidence that supports it.

## The model

We model business firms as classes consisting of a random number of units of variable size. The number of units is defined as in the Simon model (2). The size of the units evolves according to the Gibrat's growth process (3).

Firms grow by capturing new business opportunities and the probability that a new opportunity is assigned to a given firm is proportional to the number of opportunities it has already got (2; 4; 5). At each time  $t$  a new opportunity is assigned.

With probability  $b$ , the new opportunity is taken up by a new firm, so that the average number of firms at time  $t$  is  $N(t) = N(0) + bt$ .

With probability  $1-b$ , the new opportunity is captured by an active firm  $\alpha$  with probability  $P_\alpha = (1-b)K_\alpha(t)/t$ , where  $K_\alpha(t)$  is the number of units of firm  $\alpha$  at time  $t$ .

In the absence of the entry of new firms ( $b = 0$ ) the probability distribution of the number of the units in the firms at large  $t$ , i.e. the distribution  $P(K)$ , is exponential:

$$P(K) \approx \frac{1}{K(t)} \exp(-K/K(t)), \quad [1]$$

where  $K(t) = [n(0) + t]/N(0)$  is the average number of units in the classes, which linearly grows with time.

If  $b > 0$ ,  $P(K)$  becomes a Yule distribution which behaves as a power law for small  $K$ :

$$P(K) \sim K^{-\varphi}, \quad [2]$$

where  $\varphi = 2+b/(1-b) \geq 2$ , followed by the exponential decay of Eq. (1) for large  $K$  with  $K(t) = [n(0) + t]^{1-b}n(0)^b/N(0)$  (2; 6).

In the Simon model opportunities are assumed to be of unit size so that  $S_\alpha(t) = K_\alpha(t)$ . On the contrary we assume that each opportunity has randomly determined but finite size. In order to capture new opportunities firms launch new products, open up new establishments, divisions or units. Each opportunity is assigned to exactly one firm and the size of the firm is measured by the sum of the sizes of the opportunities it has taken up (4). In this paper we consider products as the relevant constituent parts of the companies and measure their size in terms of sales, even if alternative decompositions of the firm into subunits (e.g. plants, divisions) and measures of size (e.g. the number of employees, total assets) can be applied.

At time  $t$ , the size of each product  $\xi_i(t) > 0$  is decreased or increased by a random factor  $\eta_i(t) > 0$  so that

$$\xi_i(t+1) = \xi_i(t) \eta_i(t), \quad [3]$$

where  $\eta_i(t)$ , the growth rate of product  $i$ , is independent random variable taken from a distribution  $P_\eta(\eta_i)$ , which has finite mean and standard deviation.

Thus at time  $t$  a firm  $\alpha$  has  $K_\alpha(t)$  products of size  $\xi_i(t)$ ,  $i = 1, 2, \dots, K_\alpha(t)$  so that its total size is defined as the sum of the sales of its products  $S_\alpha(t) \equiv \sum_{i=1}^{K_\alpha(t)} \xi_i(t)$  and its growth rate is measured as  $g = \log(S_\alpha(t+1)/S_\alpha(t))$ .

The probability distribution of firm growth rates  $P(g)$  is given by

$$P(g) \equiv \sum_{K=1}^{\infty} P(K)P(g|K), \quad [4]$$

where  $P(g|K)$  is the distribution of the growth rates for a firm consisting of  $K$  products. Using central limit theorem, one can show that for large  $K$  and small  $g$ ,  $P(g|K)$  converge to a Gaussian distribution

$$P(g|K) \approx \frac{\sqrt{K}}{\sqrt{2\pi V}} \exp\left(-\frac{(g-m)^2 K}{2V}\right), \quad [5]$$

where  $V$  and  $m$  are functions of the distributions  $P_\xi$  and  $P_\eta$ . For the most natural assumption of the Gibrat process for the sizes of the products these distributions are lognormal:

$$P_\xi(\xi_i) = \frac{1}{\sqrt{2\pi V_\xi}} \frac{1}{\xi_i} \exp\left(-(\ln \xi_i - m_\xi)^2 / 2V_\xi\right), \quad [6]$$

$$P_\eta(\eta_i) = \frac{1}{\sqrt{2\pi V_\eta}} \frac{1}{\eta_i} \exp\left(-(\ln \eta_i - m_\eta)^2 / 2V_\eta\right). \quad [7]$$

In this case,

$$m = m_\eta + V_\eta/2 \quad [8]$$

and

$$V \equiv K\sigma^2 = \exp(V_\xi)(\exp(V_\eta) - 1), \quad [9]$$

but for large  $V_\xi$  the convergence to a Gaussian is an extremely slow process. Assuming that the convergence is achieved, one can analytically show (1) that  $P(g)$  has similar behavior to the Laplace distribution for small  $g$  i.e.  $P(g) \approx \exp(-\sqrt{2}|g|/\sqrt{V})/\sqrt{2V}$ , while for large  $g$   $P(g)$  has power law wings  $P(g) \sim g^{-3}$  which are eventually truncated for  $g \rightarrow \infty$  by the distribution  $P_\eta$  of the growth rate of a single product.

Using the fact that the  $n$ -th moment of the lognormal distribution

$$P_x(x) = \frac{1}{\sqrt{2\pi V_x}} \frac{1}{x} \exp\left(-(\ln x - m_x)^2 / 2V_x\right), \quad [10]$$

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is equal to

$$\mu_{n,x} \equiv \langle x^n \rangle = \exp(nm_x + n^2 V_x/2) \quad [11]$$

we can make an expansion of a logarithmic growth rate in inverse powers of  $K$ :

$$\begin{aligned} g &= \ln \frac{\sum_{i=1}^K \xi_i \eta_i}{\sum_{i=1}^K \xi_i} \\ &= \ln \mu_{1,\eta} + \ln \left( 1 + \frac{A}{K(1+B/K)} \right) \\ &= m_\eta + \frac{V_\eta}{2} + \frac{A(1-B/K+B^2/K^2\ldots)}{K} \\ &\quad - \frac{A^2(1-B/K+B^2/K^2\ldots)^2}{2K^2} + \ldots \\ &= m_\eta + \frac{V_\eta}{2} + \frac{A}{K} - \frac{AB+A^2/2}{K^2} + O(K^{-3}) \end{aligned}$$

where

$$A = \frac{\sum_{i=1}^K \xi_i (\eta_i - \mu_{1,\eta})}{\mu_{1,\eta} \mu_{1,\xi}} \quad [12]$$

$$B = \frac{\sum_{i=1}^K \xi_i - \mu_{1,\xi}}{\mu_{1,\xi}}. \quad [13]$$

Using the assumptions that  $\xi_i$  and  $\eta_i$  are independent:  $\langle \xi_i \eta_i \rangle = \langle \xi_i \rangle \langle \eta_i \rangle$ ,  $\langle \eta_i \eta_j \rangle = \langle \eta_i \rangle \langle \eta_j \rangle$ , and  $\langle \xi_i \xi_j \rangle = \langle \xi_i \rangle \langle \xi_j \rangle$  for  $i \neq j$ , we find  $\langle A \rangle = 0$ ,  $\langle AB \rangle = 0$ ,  $\langle A^2 \rangle = CK$ , where  $C = a(b-1)$  with  $a = \exp(V_\xi)$  and  $b = \exp(V_\eta)$ . Thus

$$\begin{aligned} \mu &= \langle g \rangle = \sum_{n=0}^{\infty} \frac{m_n}{K^n} \\ \sigma^2 &= \langle g^2 \rangle - \mu^2 = \sum_{n=1}^{\infty} \frac{V_n}{K^n}, \end{aligned} \quad [14]$$

where  $m_0 = m_\eta + V_\eta/2$ ,  $m_1 = -C/2$ ,  $V_1 = C$ ,  $V_2 = C[a(5b+1)/2 - 1 - a^2b(b+1)]$ . The higher terms involve terms like  $\langle A^n \rangle/K^n$ , which will become sums of various products  $\langle \xi_i^k (\eta_i - \mu_{1,\eta})^k \rangle$ , where  $2 \leq k \leq n$ . The contribution from  $k = n$  has exactly  $K$  terms of  $\mu_{n,\xi} \mu_{1,\xi}^{-n} \sum_{j=0}^n \mu_{j,\eta} \mu_{1,\eta}^{-j} (-1)^{n-j} \binom{j}{n}$  with  $\mu_{j,x} \mu_{1,x}^{-j} = \exp(V_x j(j-1)/2)$ . Thus there are contributions to  $m_n$  and  $V_n$  which grow as  $(ab)^{n(n+1)/2}$  with  $ab > 1$ , which is faster than the  $n$ -th power of any  $\lambda > 0$ . The radius of convergence of the expansions (14) is equal to zero, and these expansions have only a formal asymptotic meaning for  $K \rightarrow \infty$ . However, these expansions demonstrate that  $\mu$  and  $\sigma$  do not depend on  $m_\eta$  and  $m_\xi$  except for the leading term in  $\mu$ :  $m_0 = m_\eta + V_\eta/2$ .

Not being able to derive close-form expressions for  $\sigma$  we perform extensive computer simulations, in which  $\xi$  and  $\eta$  are independent random variables taken from lognormal distributions  $P_\xi$  and  $P_\eta$  with various  $V_\xi$  and  $V_\eta$  (Fig. 1 and 2).

## The Empirical Evidence

The model relies upon the assumptions of independence of the growth of products from each other and from the number of products  $K$ . However, these assumptions could be violated and at least three alternative explanations must be analyzed:

1. *Size dependence.* The probability that an active firm captures a new market opportunity is more or less than proportional to its current size. In particular, there could be

a positive relationship between the number of products of firm  $\alpha$  ( $K_\alpha$ ) and the size ( $\xi_i(\alpha)$ ) and growth ( $\eta_i(\alpha)$ ) of its component parts due to monopolistic effects and economies of scale and scope. If large and small companies do not get access to the same distribution of market opportunities, large firms can be riskier than small firms simply because they tend to capture bigger opportunities.

2. *Units interdependence.* The growth processes of the constituent parts of a firm are not independent. One could expect product growth rates to be positively correlated at the level of firm portfolios, due to product similarities and common management, and negatively correlated at the level of relevant markets, due to substitution effects and competition. Based on these arguments, one would predict large companies to be less risky than small companies because their product portfolios tend to be more diversified.
3. *Time dependence.* The growth of firms constituent units does not follow a pure Gibrat process due to serial autocorrelation and lifecycles. Young products and firms are supposed to be more volatile than predicted by the Gibrat's Law due to learning effects. If large firms are older and have more mature products, they should be less risky than small firms. On the contrary, ageing and obsolescence would imply that incumbent firms are more unstable than newcomers.

The first two hypotheses are not falsified by our data (Fig. 3).

The number of products of a firm and their average size defined as  $\langle \xi(K) \rangle = \langle \frac{1}{K} \sum_{i=1}^K \xi_i \rangle$ , where  $\langle \rangle$  indicates averaging over all companies with  $K$  products, has an approximate power law dependence  $\langle \xi(K) \rangle \sim K^\gamma$ , where  $\gamma = 0.38$ .

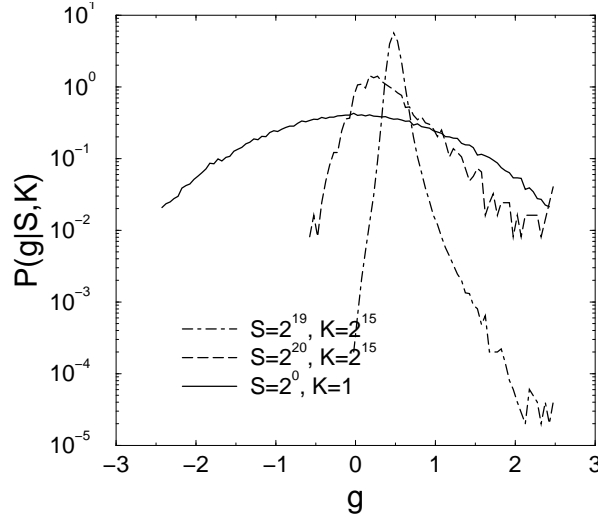
The mean correlation coefficient of product growth rates at the firm level  $\langle \rho(K) \rangle$  shows an approximate power law dependence  $\langle \rho(K) \rangle \sim K^\zeta$ , where  $\zeta = -0.36$ .

Since larger firms are composed by bigger products and are more diversified than small firms the two effects compensate each other. Thus if products are randomly reassigned to companies, the size variance relationship will not change.

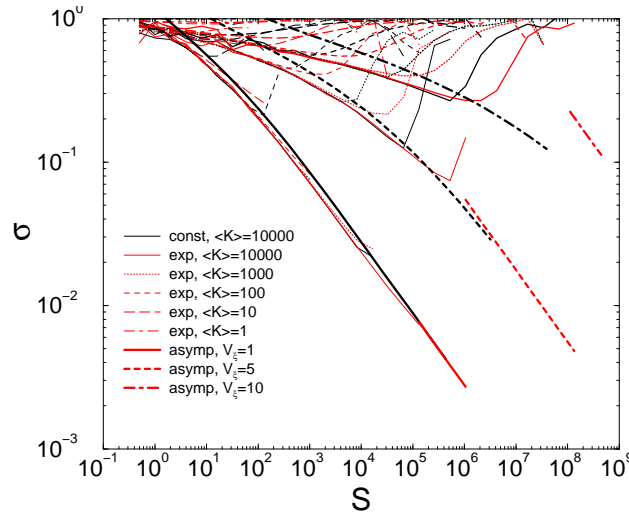
As for the time dependence hypothesis, despite there are some departures from a Gibrat process at the product level (Fig. 4) due to lifecycles and seasonal effects, they are too weak to account for the size variance relationship. Moreover asynchronous product lifecycles are washed out upon aggregation.

## References

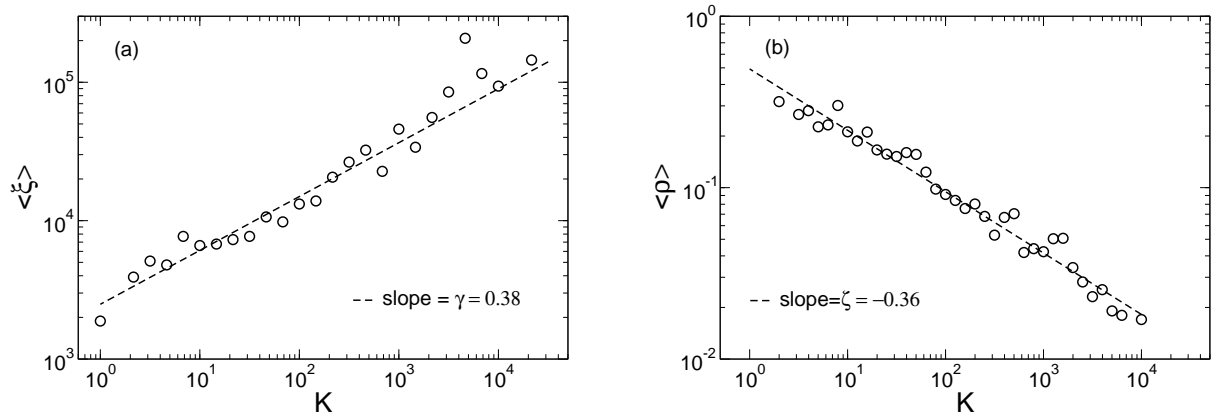
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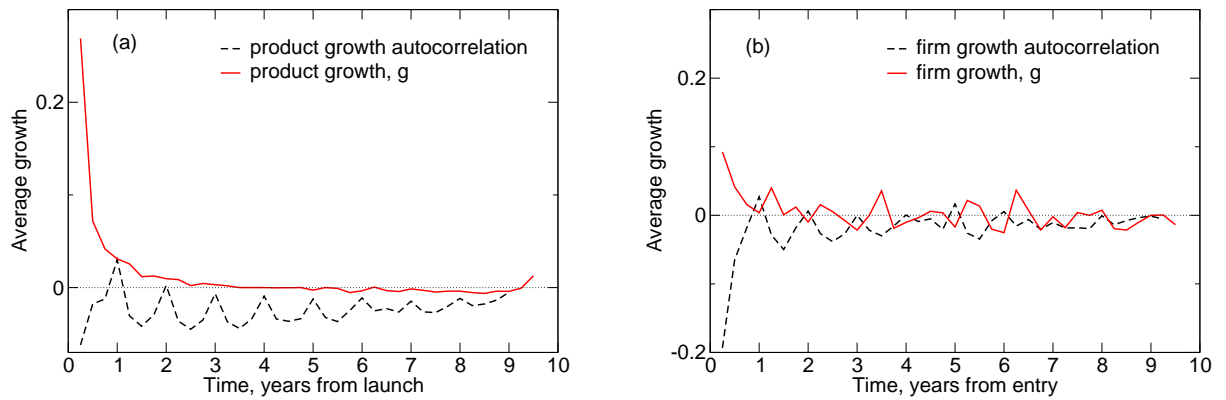
**Fig. 1.** Simulation results for the conditional growth rate distribution  $P(g|S, K)$  for the case of lognormal  $P_\xi$  and  $P_\eta$ , with  $V_\xi = 6$ ,  $V_\eta = 1$  and  $m_\xi = m_\eta = 0$ . For  $K = 1$  the distribution is perfectly Gaussian with  $V_\eta = 1$  and  $m_\eta = 0$ . However for large  $K$  the distribution develops a tent-shape form with the central part close to a Gaussian with mean  $m = 1/2$  as predicted by Eq. (8). The vast majority of firms (99.7%) have sizes in the vicinity of  $K\mu_\xi$  which for  $K = 2^{15}$  and  $\mu_\xi = \exp(m_\xi + V_\xi/2) = 20.1$  belongs to the bin  $[2^{19}, 2^{20}]$  and only 0.25% of firms belong to the next bin  $[2^{20}, 2^{21}]$ . These firms are due to a rare occurrence of extremely large products. The real number of products in these firms is  $K_e = 2.4$ , while the normally sized firms have  $K_e = 31$ . The fluctuations of these extremely large products dominate the fluctuations of the firm size and hence  $P(g|S, K)$  for such abnormally large firms is broader than for normally sized firms. Accordingly,  $\sigma = 0.09$  and  $\sigma = 0.41$  respectively for the normally sized and abnormally large firms.



**Fig. 2.** The behavior of  $\sigma(S)$  for the exponential distribution  $P(K) = \exp(-K/\langle K \rangle)/\langle K \rangle$  and lognormal  $P_\xi$  and  $P_\eta$ . We show the results for  $K_0 = 1, 10, 100, 1000, 10000$  and  $V_\xi = 1, 5, 10$ . The graphs  $\sigma(K_S)$  and the asymptote given by  $\sigma(S) = \sqrt{V/K_S} = \frac{\exp(3V_\xi/4 + m_\xi/2)\sqrt{\exp(V_\eta)-1}}{\sqrt{S}}$  are also given to illustrate our theoretical considerations. One can see that for  $V_\xi = 1$ ,  $\sigma(S)$  almost perfectly follows  $\sigma(K_S)$  even for  $\langle K \rangle = 10$ . However for  $V_\xi = 5$ , the deviations become large and  $\sigma(S)$  converges to  $\sigma(K_S)$  only for  $\langle K \rangle > 100$ . For  $V_\xi = 10$  the convergence is never achieved.



**Fig. 3.** (a) The relationship between the average product size and the number of products of the firm. The log-log plot of  $\langle \xi(K) \rangle$  vs.  $K$  shows power law dependence  $\langle \xi(K) \rangle \sim K^{0.38}$ . (b) The relationship between the mean correlation coefficient of product growth rates and the number of products of a firm. The log-log plot of  $\langle \rho(K) \rangle$  vs.  $K$  shows power law dependence  $\langle \rho(K) \rangle \sim K^{-0.36}$ .



**Fig. 4.** (a) The average growth and the auto-correlation coefficient of products since launch. Products growth tend to be higher in the first two years from entry. We detect seasonal cycles and a weak (not significant) negative auto-correlation. (b) The average growth rate and the auto-correlation coefficient of firms from entry. The departures of product growth from a Gibrat process are washed out upon aggregation. The growth rates do not depend on age and do not show a significant auto-correlation.